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A roadmap for the introduction of gaseous transport fuel: A case study for renewable natural gas in Ireland

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ABSTRACT

Ireland is heavily dependent on imported transport fuel. The bill in 2008 was €5.9 billion. Because of the significant resources in organic residues and feedstocks there is readily available potential to substitute 8.4% of oil with indigenously produced biomethane, a renewable gaseous transport fuel. This level of oil replacement with biomethane would directly save €500 m a^{-1} from imports, provide an injection of €500 m a^{-1} into the Irish economy and save a further €22 m a^{-1} in the reduced damage cost of traffic-related pollutant. The EU Renewable Energy Directive allows a double credit for biofuels produced from residues or lignocellulosic material. Thus the biomethane industry will allow compliance with the renewable energy supply in transport target of 10% in 2020 and the EU Landfill Directive. Biomethane is predicated on a compressed natural gas (CNG) industry. The grid in Ireland is extensive reaching 40% of all houses. However, development of this industry in Ireland requires strong government commitment. Recommended supports include: policy dictating that all new buses run on gaseous fuel; setting a market penetration target for CNG vehicles; mandation of biomethane as a proportion of gaseous transport fuel, subsidies for biomethane facilities and grid injection.

Contents

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1. Introduction

1.1. Gaseous transport fuels

The age of oil is coming to an end. In 2050, oil will play a small role in the low carbon economy. Whether we have reached peak oil or are heading for peak oil is relatively immaterial; oil and its derivatives will become increasingly more expensive. We need new sources of energy. It is often suggested that gas will become dominant when oil goes into decline. The hydrogen economy is mooted by many but this is some way away. An issue with hydrogen is that it is primarily an energy carrier. Hydrogen though plentiful in the world is difficult to isolate. Hydrogen may be sourced from natural gas or biogas, but the energy requirement to process methane to hydrogen is significant. Hydrogen has a very high energy value per unit of mass, but because of its density it has a relatively low energy per unit of volume. The end result of the conversion from methane to hydrogen is the transformation of a gas from 37.8 MJ/m_n^3 to 12.1 MJ/m_n^3; the energy per unit of volume is reduced by a factor of 3. For vehicle fuel this suggests either a threefold decrease in km per unit of storage or greater energy demand in compressing hydrogen. As a result natural gas and biomethane are currently the preferred gaseous transport fuel; the technology is mature with 12 million vehicles on the road. From gas field to vehicle natural gas requires very little processing to make it appropriate for use as a fuel. The technology associated with compressed natural gas (CNG) is simple and mature and gas is a clean-burning fuel. Natural gas may be viewed as an easy transition to biomethane and eventually maybe to bio-hydrogen.

1.2. The Irish transport sector

1.2.1. Energy and fuels used in Ireland

The rapid growth of the Irish economy since the early 1990s has resulted in a significant expansion of the transport sector. The number of road vehicles exceeded 2 million in 2004; this equates to over 500 vehicles per 1000 population. Private passenger cars only account for 77% of total road vehicles; the remainder are goods vehicles and public service vehicles. Petrol fuels 63% of the private fleet [1]. However, petrol consumption is less than diesel consumption due to the high demand of diesel in goods and public service vehicles (petrol 73 PJ; diesel 104 PJ in 2009) [2]. Energy required for transport in Ireland increased by 151% over the period 1990–2009, while the greenhouse gases (GHG) emitted from transport increased by 149%. This shows almost no improvement in the GHG reduction per MJ of energy consumed. Imported oil accounts for 98% of total transport energy [2]. The Sustainable Energy Authority of Ireland (SEAI) predicts a slight decrease in the demand of road transport energy between 2009 and 2020 (180 PJ as opposed to 178 PJ) due to the present economic downturn [3]. EU legislation mandates Ireland to reduce 20% of its GHG emissions relative to 2005 by 2020 [4]. A long-term target for 2050 is a reduction in GHG by 80% below 1990 levels [5]. These targets are extremely challenging and set the demand for a low-carbon economy.

1.2.2. Renewable energy sources in transport (RES-T) in Ireland

Ethanol and biodiesel are the dominant biofuels in Ireland. The Biofuels Obligation mandated a volumetric blend of at least 4% biofuels in retail motor fuels in 2010 [6]. The obligation aims to increase the blend to a level that will allow compliance with the EU Renewable Energy Directive target of 10% RES-T in 2020 [7]. Arable land is limited in Ireland to 9% of total agricultural land and this is already fully utilised for food and beverage production [8]. As a result, the majority of ethanol and biodiesel utilised is currently imported. A target is in place whereby 10% of all vehicles will be electric vehicles (EVs) by 2020 [9]. SEAI expects the 10% RES-T target for 2020 to be met by 9% biofuels and 1% EVs [3]. If biofuels are not produced indigenously the level of dependency on imported fuels will remain at a similar level to 2009. Air quality is also of concern for the larger cities in Ireland. The Environmental Protection Agency (EPA) reported that NO_x and PM limits exceeded allowable limits in the city centres of Dublin and Cork [10].

1.3. Scope of the study

CNG is a lower carbon fuel than petrol and diesel. Bio-CNG (blend of natural gas with biomethane) is lower carbon than CNG. Thus two industries are required for a bio-CNG industry: a biomethane industry and a CNG industry. The biomethane industry generates biogas, upgrades to biomethane and injects to the gas grid, while the CNG industry distributes and serves gaseous transport fuel. Technical, economic and environmental analyses of biomethane as a transport fuel have previously been examined [8,11–13]. This paper is concerned with the mechanism of initiation of a gaseous transport fuel industry. It concerns itself with: indigenous resources; infrastructure; policy and regulations. It examines the experience in countries (Germany and Sweden) where gaseous renewable fuel has been implemented with success. The objectives of the paper are as follows.

Table 1
Potential for biomethane production in Ireland estimated for 2020.

Source	Technical potential[a]	Baseline potential[a]	Contribution of baseline energy to the total demand of 178.2 PJ[b]
Agricultural slurry	15.53 PJ	1.88 PJ	1.05% × 2 (double credit) = 2.1%
OFMSW	2.26 PJ	0.57 PJ	0.32% × 2 (double credit) = 0.64%
Slaughter waste	1.37 PJ	0.68 PJ	0.38% × 2 (double credit) = 0.76%
Surplus grass	47.58 PJ	11.9 PJ	6.68% × 2 (double credit) = 13.36%
Total	66.74 PJ	15.03 PJ	8.43% × 2 (double credit) = 16.9%

[a] From [8].
[b] From [3].

- Highlight the potential benefits of bio-CNG as a transport fuel.
- Assess the barriers to the industry.
- Suggest a road map for the industry in Ireland.

2. Utilising bio-CNG as a transport fuel in Ireland

2.1. Potential of bio-CNG

2.1.1. Biomethane resources

Biomethane is biogas purified to a high methane content (≥97% CH_4), with trace contaminants such as hydrogen sulphide removed. Biogas can be produced from various organic compounds using the anaerobic digestion process. A study by Singh et al. suggested that there is a practical potential to produce 15 PJ a^{-1} of biomethane in 2020 from agricultural slurry, organic fraction of municipal solid waste (OFMSW), slaughter waste and surplus grass in Ireland (Table 1) [8]. This would equate to the amount of fuel utilised by 390,000 cars a^{-1} (38 GJ car^{-1} a^{-1} or 1282 L of petrol a^{-1} or fuel used by petrol car travelling 18,000 km a^{-1} at a fuel efficiency of 7 km L^{-1}). This equates to 19.5% of the vehicle stock (2 million vehicles) and 25% of the private car fleet (1.54 million private cars). The feedstock for the fuel should not impact on food production as it does not require any arable land. In accordance with the EU Renewable Energy Directive [7] biofuels produced from residues and lignocellulosic material (such as grass) receive double credit towards the 2020 RES-T target. From Table 1, 10% RES-T is equivalent to 17.8 PJ. Biomethane can readily supply 15 PJ or 8.4% of energy in transport; allowing for the double credit biomethane can satisfy 17% RES-T.

2.1.2. Natural gas infrastructure

In Germany, biomethane from biogas facilities is injected into the natural gas grid. This may be used by households and refuelling stations as renewable energy. In essence it is irrelevant from where the gas is removed on the grid as long as there is an accounting process between the user and the supplier. Thus the distribution system is already in place. This concept is very applicable to Ireland due to the existing extensive natural gas pipeline network. The natural gas system in Ireland covers 10,000 km of distribution pipeline and 2500 km of transmission pipeline. It is connected to the European gas network through the interconnector with Scotland. At present the distribution network supplies natural gas to 620,000 homes and 24,000 commercial enterprises in 153 towns of 19 counties [14]. At least 40% of the population have access to natural gas in their homes. This may be contrasted with Sweden where biomethane has been successfully introduced (Fig. 1). The gas network in Sweden is only in the west. The eastern cities including Stockholm, Linkoping, Norkoping and Upsala all utilise biomethane with the disadvantage of not having a gas grid. This requires the costly distribution (both financial and in terms of energy balance) through compression in containers which are transported to the service station on the back of a lorry. Ireland has a distinct advantage over Sweden in the distribution system.

2.1.3. CNG: a mature technology

At present there are more than 12 million CNG vehicles on the road worldwide; Europe has over 1.3 million CNG vehicles. There are almost 18,000 CNG refuelling stations in 83 countries. Pakistan, Iran and Argentina are the leading countries with 2.6, 2 and 1.8 million CNG vehicles, respectively. In Europe, there are 700,000 CNG vehicles in Italy, 200,000 in Ukraine, and 100,000 in Armenia and Russia. Replacing diesel buses with CNG buses is a widespread practice in a number of global and European cities, with more than 400,000 CNG buses in operation [17]. The customer has a choice between an original equipment manufacturer (OEM) and retrofit aftermarket equipment; mono-fuel, bi-fuel and dual fuel engine. There is also a choice of refuelling between fast fill and slow fill; public refuelling or private and home refuelling [18].

2.2. Benefits of bio-CNG

2.2.1. Indigenous production of transport fuel

First generation biofuels such as ethanol and biodiesel cannot be produced in Ireland to a significant level due to the limited arable land. For example a 150 million litre per annum facility would require 400,000 t of wheat grain (375 L ethanol per tonne of wheat grain) or 47,000 ha of arable land (8.4 t wheat grain ha^{-1}). This suggests that 12% of all arable land (400 kha) is required to generate less than 2% of energy in transport (3.17 PJ/178 PJ). [19]. Technologies for second generation biofuels are unlikely to be commercially available in Ireland by 2020. Ireland has limited feedstock for second generation biofuel, with limited straw production (imports 20% of all grain requirements) and only 10% of land under forest (one of the lowest levels in Europe) [20]. The choices for Ireland are either importing more liquid biofuels or producing indigenous biomethane. Biomethane is an indigenous biofuel that can satisfy the 10% RES-T target without impinging on food supply. Compressed biomethane would result in a decreased dependence on the international oil market and an improved security of supply. Biomethane can also be coupled with the indigenous natural gas resource [21]. Ireland has no indigenous production of oil.

2.2.2. GHG emissions and air pollution

Well-to-wheel (WTW) studies suggest that CNG has a lower GHG emission per kilometre travelled than petrol or diesel (18–38% and 2–21% reductions, respectively) [22–24]. Bio-CNG benefits further because of the GHG saving credit attributed to biomethane. Table 2 (adapted from the EU Renewable Energy Directive [7]) outlines the GHG savings (typical and default values) of selected biofuel systems. Default values are applied when no analysis is carried out by the developer. Typical values are what would be expected if an analysis were carried out. The Directive stipulates a minimum 60% savings as compared to the displaced fossil fuel if the biofuel can be considered a biofuel to satisfy the 2020 RES-T target [7]. The GHG savings of wheat ethanol, sugar beet ethanol and rape seed biodiesel which may be produced indigenously in Ireland are not comparable to biomethane. Biomethane is sustainable and it

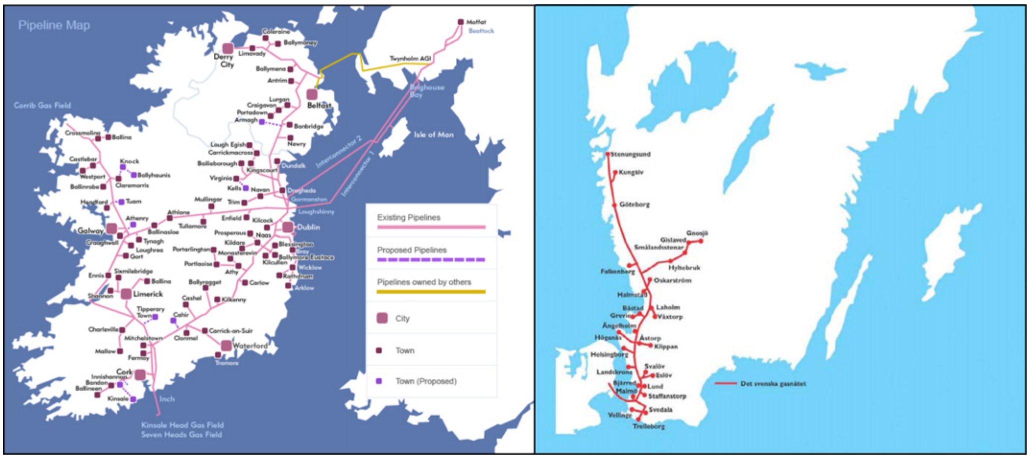

Fig. 1. Gas pipeline network in Ireland (left) [15] and Sweden (right) [16].

produces only about 20% of GHG emitted by fossil fuel. Using 10% biomethane in a blend with natural gas offsets the GHG saving by about 8% relative to CNG. The benefit of bio-CNG also includes an improvement in the local air quality within urban areas which are normally associated with traffic congestion. CNG reduces emissions such as CO, HC, PM, NO_x, SO_2, benzene, 1,3-butadiene. [18,25,26].

2.2.3. Anaerobic digestion and waste management

Ireland produces 35 million $t\,a^{-1}$ of organic waste that can be treated in anaerobic digesters. This includes 34 million $t\,a^{-1}$ of agricultural slurry, 0.8 million $t\,a^{-1}$ of OFMSW and 0.4 million $t\,a^{-1}$ of slaughter waste [8]. The agricultural sector and the waste sector in Ireland are responsible for 27% and 2% of national GHG, respectively [27]. Treating these organic wastes through anaerobic digestion can significantly reduce GHG emissions and significantly reduce quantities sent to landfill. The digestate from the digestion process conserves nutrients, which can be used as bio-fertilizer replacing chemical fertilizer; this also results in lower N_2O emission because of the low volatility associated with well digested feedstock [28]. The digestate from the anaerobic digestion process has less odour and ammonia emissions, and also reduces the risk of polluting waterways with nitrates and pathogens. Anaerobic digestion results in minimization of environmental impacts coupled with the benefit of energy production.

2.2.4. Social and economic opportunities

There are less than 20 anaerobic digesters in operation in Ireland. The majority of these treat industrial wastewater or sewage sludge and use the produced biogas for heat or combined heat and power (CHP) [29]. Fig. 2 shows the full participation model of stakeholders in the bio-natural gas industry; it highlights what is in place and what is not in place. The industry is complex and relies on symbiotic relationships. Formation of the industry will bring in more stakeholders from different areas of expertise that will need to work together and create relationships. Ireland has a potential to build 190 digesters by 2020 with a capacity of ca. 50,000 $t\,a^{-1}$ each; this size is required to allow scale for cost efficient biomethane upgrading [8]. This industry could directly employ 570 (3 per facility) and indirectly employ 4000 (21 per facility) in construction of facilities, servicing of M&E, transport of feedstocks and digestate, processing of feedstocks, etc. There is significant potential for additional jobs along the supply chain of a bio-natural gas industry including for: design and fabrication of elements of the biomethane infrastructure; design and construction of new service stations; servicing the new fleet of CNG vehicles; growing energy crops and processing waste materials for feedstock. Ireland spent €5.9 billion in transport fuel in 2008 [30]. Replacing 8.4% of oil with biomethane would directly save €500 $m\,a^{-1}$ from imports and in turn provide an injection of €500 $m\,a^{-1}$ into the Irish economy. The low price of natural gas (compared to petroleum) will also help to reduce import cost. The benefits also include savings in the public health sector. The damage cost of traffic-related pollutant in Ireland in 2008 is calculated to be €423 m (Table 3). The replacement of diesel vehicles by CNG vehicles can reduce significant damage cost with up to 67%, 90% and 97% reduction in NO_x, SO_2 and PM respectively. Replacement of 8.4% transport fuel with CNG may save €22 $m\,a^{-1}$ (Table 3).

There is also significant opportunity for a development in intellectual property (IP) and innovation. A number of counties such as New Zealand, India, China and South Korea became technology exporters after initiating a CNG industry [35].

Table 2
Typical and default GHG savings for various biofuel systems [7].

Biofuel production pathway	Typical GHG savings (%)	Default GHG savings (%)
Wheat ethanol	32	16
Rape seed biodiesel	45	38
Sugar beet ethanol	61	52
Palm oil biodiesel	62	56
Sugar cane ethanol	71	71
Biomethane from OFMSW as CNG	80	73
Biomethane from wet manure as CNG	84	81
Biomethane from dry manure as CNG	86	82

3. Barriers to industry development

3.1. Policy and regulation in biogas industry

Despite the potential of biomethane and bio-CNG, the development of the industry in Ireland is slow. The reasons for this malaise are suggested below [36–38].

3.1.1. Legislation and policy related to the municipal waste sector

There is an uncertainty in the waste sector regarding preferred technologies, policies, waste ownership and collection contracts. For example, at present in Dublin the local authorities have a contract with a developer to construct a 600,000 $t\,a^{-1}$ incinerator. However, the waste collection is privatised and these waste collectors wish to construct their own waste treatment systems predominately employing Material Biological Treatment (MBT) systems. This is at present in the courts. Cohesive legislation and policy is required.

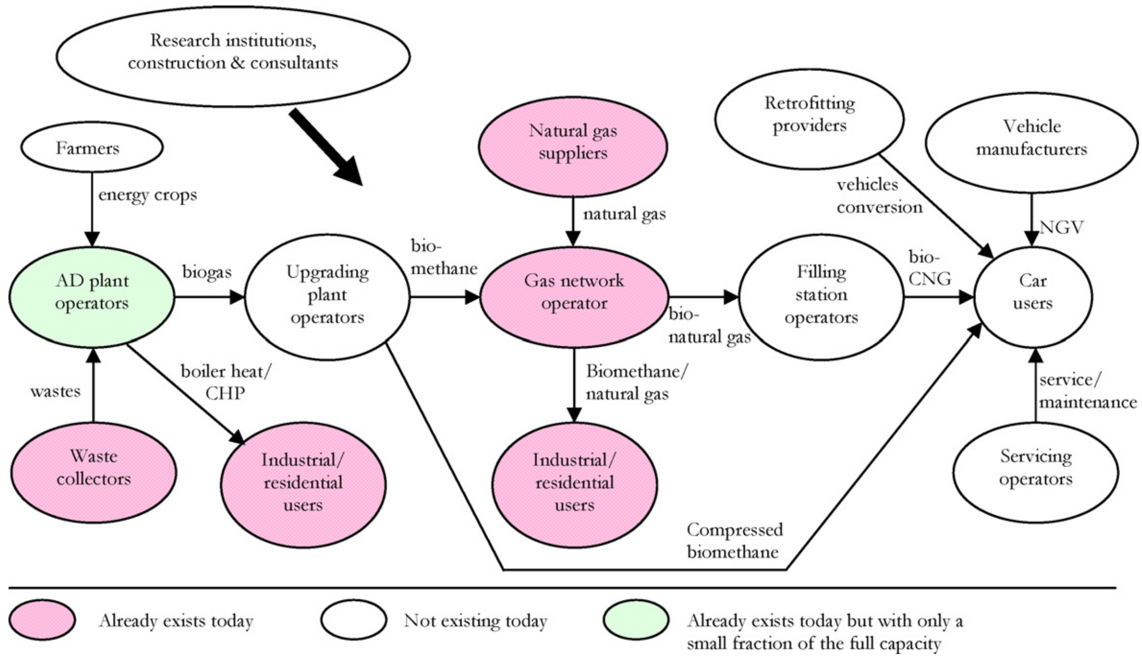

Fig. 2. Model of the bio-natural gas industry.

3.1.2. Interpretation of Animal By-products (ABPs) Regulations

The processing of feedstock and disposal of digestate are strictly controlled by the national interpretation of the Animal By-products Regulations [39]. For example, in Ireland agricultural slurry requires pasteurisation if the slurry is to be spread on a different farm. Digestate must also be stored for 6 months at the biogas facility. Neither of these requirements would be required in other EU states. This adds a considerable cost to the biogas industry in Ireland.

3.1.3. Legal authorisation

Developing a large-scale biogas plant requires an acceptance from local authorities and community. Issues relate to traffic control, health and safety and existing road infrastructure. There tends to be ignorance and fear of gas related industries that impedes on the legal authorisation to build such a facility. The legal authorisation is complicated by its multiple natures. Not only does the developer need to liaise with the local authority (planning for construction and infrastructure), but also The Environmental Protection Agency (for a waste license) and The Department of Agriculture (biogas facility and spreading of digestate).

3.1.4. Tariff structure of CHP and biomethane injection

At present there is a tariff structure in place for biogas to combined heat and power (CHP). The tariff is relatively crude in that the same tariff is paid regardless of whether a gate fee is received for the feedstock or not. The financial viability of energy crop digestion is heavily dependent on heat markets and subsidies. For grid injection there is currently no tariff structure in place, although the development of such a structure is underway.

3.1.5. Legislation supporting biomethane injection

Directive 2009/73/EC [40] states that biogas should be granted non-discriminatory access to the gas grid. Biomethane is currently injected into the gas grid in a number of EU countries, but there is currently no legislation (or policy) in place in Ireland to facilitate grid injection.

3.2. Policy and regulation in CNG industry

The major issue for this industry is that there is currently no market for CNG. There are only two CNG vehicles and one refuelling station in Ireland [17]. The gas pipeline infrastructure is in place, but the network of refuelling stations and vehicle service stations will need to be developed in association with a creation of demand and supply for CNG vehicles. Regulation and incentives from the government are required to build this industry.

3.3. Costs of biogas facilities

Economic viability is the most crucial incentive in commercialising an anaerobic digester. Full-scale plants processing 42,000 t a^{-1}

Table 3
Cost of damage due to human and crop exposure to traffic-related pollutant.

Pollutant	Damage cost rate[a]	Quantity[b]	Damage cost estimated for 2008	Damage cost estimated for 2020[c]	Damage cost saved by 8.4% replacement of CNG[d]
NO_x	€7500 t^{-1}	53,052 t	€397.89 m	€362.39 m	€20.4 m
SO_2	€9500 t^{-1}	507 t	€4.82 m	€4.39 m	€0.21 m
PM	€29,000 t^{-1}	697 t	€20.21 m	€18.41 m	€0.95 m
Total			€422.92 m	€385.19 m	€21.56 m

[a] From [31].
[b] From [32,33].
[c] Proportional to energy demand in road transport: 193.9 PJ in 2008 and 176.6 PJ in 2020 (exc. EVs).
[d] 67% NO_x reduction compared to petrol and diesel, 90% SO_2 and 97% PM reduction compared to diesel; 36.7% petrol and 63.3% diesel share in 2020 [34].

of maize recently commissioned in Germany cost in the region of €2 m. An additional plant for upgrading the biogas to biomethane could add a further €2 m to the capital cost [38]. This equates to approximately €95 t^{-1} a^{-1}. Capital cost for the same facilities to be built in Ireland would be expected to be higher (ca. €110 t^{-1} a^{-1}) [36]. This increase is due to interpretation of the Animal By-products Regulations, requirement for extra storage of digestate and risk associated with a new industry. A study by Smyth et al. [36] highlighted the financial difficulty associated with mono-digestion of energy crops with Irish tariffs. Gate fees charged for processing other substrates such as OFMSW, manure, and food waste can lead to financially viable energy crop co-digestion facilities.

3.4. Specific technology for grass digestion

There may be a tendency for digesters that were developed in continental Europe based on high solids content feedstocks, such as maize, to be imported to Ireland for use as grass digesters. The maize digester may not be suitable for grass digestion. Grass has specific characteristics such as its long fibrous nature (ideal for wrapping around mixers) and its tendency to float (which can inhibit the biological process) [41]. In continental Europe grass is usually co-digested with a larger proportion of animal manure or maize to overcome these difficulties. Ireland's climate is not ideal for maize and as a result yields relatively low biomass per hectare; neither is arable land abundantly available. From a technical viewpoint mono-digestion of grass or co-digestion with manure is ideal for Ireland. Grassland occupies 91% of agricultural land. Cross compliance dictates that this ratio must not change by more than 10% [8].

4. Strategy to promote bio-CNG

4.1. Policy framework for the bio-natural gas industry

The bio-CNG industry is a complex system involving stakeholders in the biogas and CNG sectors (Fig. 2). Government must provide the appropriate policy framework which offers sufficient incentives to create participation and partnership among the stakeholders [42]; it must strengthen the incentives and weaken the barriers. Lantz et al. [43] stated that the policy framework for the bio-natural gas industry may include policy objectives, legislation, taxes and financial subsidies.

4.1.1. Policy drivers

Drivers for biogas and CNG are numerous. The Kyoto Protocol which was negotiated within the United Nations is the key policy objective at international level [44]. Its expiration in 2012 for the EU will be replaced with the new emission targets proposed by the European Commission for 2020; this includes for Ireland a reduction in GHG emissions of 20% on levels in 2005 by 2020 [4]. EU directives and policy documents include for example, the Nitrate Directive [45], Animal By-product Regulation [39] and the Landfill Directive [46]. Anaerobic digestion is viewed by the EU as a multi-purpose technology with the potential to fulfil these policy objectives [47]. The use of CNG and biomethane is supported by the EU through the policy objectives for road transport which focus on securing and diversifying the energy supply for transport in the environmentally friendly and affordable manners [48]. These policy objectives may include, for example, the Air Quality Directive [49] and Renewable Energy Directive [7]. The EU has set the agenda; it is up to the EU state to decide how to meet and satisfy the targets.

4.1.2. Legislation

A realisation of the bio-natural gas industry requires encouraging legislation that provides sufficient incentives and facilitates barrier removal. Including a feed-in tariff scheme as part of the legislation fosters the growth of the biogas industry in a number of European countries. The scheme offers a direct financial benefit to biogas plants, particularly the plants with a CHP scheme. It is viewed as the key driver to promote the investment in biogas industry while minimizing the price volatility exposure for investors and small project developers [50]. For example, in Germany high financial return has stimulated the biogas industry leading to the construction of hundreds of new anaerobic digestion plants per annum [51]. The International Energy Agency (IEA) has stated that the high investor security provided by the German feed-in-tariff has been a success, resulting in a rapid deployment of renewables, the entrance of many new actors to the market and a subsequent reduction in costs [52]. The German system offers tariffs for biogas based on a number of criteria, some of which are included below in a simplified form:

- € c 11.67 kW_eh^{-1} basic compensation for biogas.
- € c 7 kW_eh^{-1} if energy crops are used as a feedstock for biogas production.
- € c 2 kW_eh^{-1} for biogas upgrading to biomethane.

Legislation, policy and suitable tariffs are required for the injection of biomethane into the natural gas grid [53,54]. Legislation is crucial to promote the CNG industry; for instance, a mandatory conversion of public fleets and buses to run on CNG [35]; obligating all new petrol stations to offer CNG in order to obtain their operating license [55]; obligating the blend of renewable fuels in the retail fuels to stimulate the use of biomethane for transport [43].

4.1.3. Taxes

Taxes can be aimed to penalise existing carbon intensive GHG emitting systems. Landfill taxes (set for €75 t^{-1} in 2013 in Ireland), taxes on chemical nitrogen fertiliser and carbon taxes on fossil fuels all enhance the anaerobic digestion industry [43]. Obviously anaerobic digestion of OFMSW benefits from a landfill tax in that the gate fee will rise with the landfill tax [56]. Carbon taxes on fossil transport fuel allows biomethane to be more financially competitive allowing for shorter payback periods on CNG vehicles [35,57]; this is enhanced by the fact that CNG at present is not subject to excise duty in the EU [36]. Vehicle registration taxes based on CO_2 emissions result in significantly lower taxes for CNG vehicles [35,54,58]. The money raised from carbon and environment taxes can be targeted to low carbon low GHG emitting alternatives [56] such as energy crop digestion. This will have the benefit of bringing employment to rural economies.

4.1.4. Financial subsidies

The high investment required to start an industry requires financial support; this may be in form of capital grants or low-interest loans. For example, in Sweden 30% of the capital cost of biogas projects were funded through government investment programmes [54]; Germany and Austria also have direct subsidies and low interest loans provided for the development of biogas projects [59]. Upgrading biogas to biomethane is expensive and a relatively new industry. The cost of the produced biomethane could readily be two to three times more expensive than natural gas; again subsidies are required to start the industry [53]. Grid access may be subsidised by the grid operator or covered by a public service obligation [60]. The lack of excise duty on gas as a propellant may of itself be sufficient to allow biomethane be cost competitive with petrol and diesel [36,61] (Table 4). In Germany taxis and fleet cabs get special rates for refuelling CNG in some municipalities [58]. In

Table 4
Comparison of vehicle fuel costs adapted from [36].

Fuel	Unit cost	Energy value ($MJ L^{-1}$)	Cost per unit energy (€$c MJ^{-1}$)
Petrol[a]	€$1.224 L^{-1}$	30	4.08
Diesel[a]	€$1.150 L^{-1}$	37.4	3.07
Compressed grass biomethane[b]	€$0.96 m^{-3}$	37	2.60
CNG – UK[b]	€$0.71 m^{-3}$	37	1.92
Bio-CNG[c]	€$0.74 m^{-3}$	37	1.99

[a] Price of petrol and diesel is the price at the pumps and includes for excise duty and VAT.
[b] Gas as a propellant is free from excise duty. VAT is charged at 21%.
[c] Bio-CNG price calculated using UK CNG prices and a blend of 10% biomethane, 90% CNG.

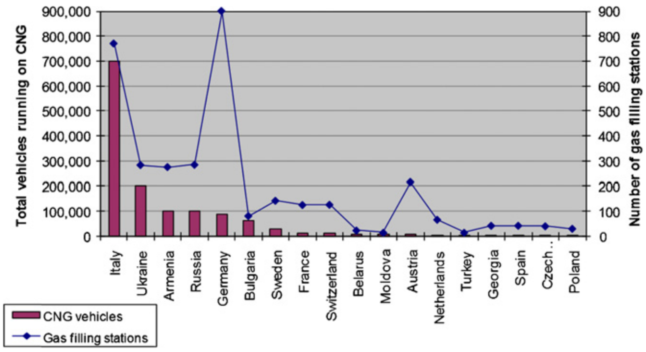

Fig. 3. Ratio of CNG vehicles to CNG service stations in Europe [17].

Sweden CNG cars are exempted from congestion tax; CNG vehicles may also avail of free parking in cities [54]. Subsidies for new CNG cars and home refuelling systems also create incentives for the users [35].

4.2. Infrastructure, financial and technical support

4.2.1. The biogas industry

The business plan for a biogas plant must consider a number of factors which may include: source and cost of feedstock; plant capacity; plant location; spread lands for digestate; usage of produced energy; transport and logistics; and investment risk [50]. Investment risk is associated with policy, regulations and the market for biogas. It is not part of the engineering design. However removal of excise relief, changing of landfill tax and new feed-in tariffs all have massive implications on the viability of the biogas industry. Financing of a biogas plant requires "bankability"; guaranteed income for a fixed period of time. Uncertainty in tariffs, short-term tariffs, lack of clarity on landfill tax (and hence gate fees) are investment risks that affect payback period and hence the "bankability" of the project.

The sale of biomethane produced from a stand-alone upgrading plant depends on the vehicle gas demand in the CNG market. Short period excise relief schemes impact greatly on the financial viability of the biomethane transport fuel industry. It is preferable to mandate renewable gas (biomethane) as a portion of gaseous fuel sales.

A new industry will always carry uncertainty, "unknown unknowns". Fuller knowledge of technical issues takes time and mistakes. There are a wide range of companies, manufacturers and suppliers in this industry providing technical advice, training, products and services [62] but these are not sited in the country which is introducing the technology. Though anaerobic digestion is a mature technology there is still significant requirement for R&D in various feedstocks, pretreatments, enzymes, reactor configuration and IT. The majority of full-scale biogas plants are not optimised as full knowledge of the real time biological process available in the laboratory is not available in full scale facilities [63]; wireless sensors and IT systems are required to modernise bioreactors and allow more aggressive loading and resultant smaller more sophisticated digesters. Characteristic of some substrates such as grass also causes difficulties for the operation even in the laboratory scale [41]. Care must be taken as grass silage is not the same in all countries. In Austria grass silage is wilted and a dry solids content of 40% is readily attainable; in temperate climates with wet summers (such as Ireland) grass silage may have a dry solids content of 20% [52]. This has huge implications for the digester design. Much work is required in up-scaling laboratory designs into full-scale digester systems. Digestate is a crucial concern in digester systems. Connecting feedstocks (and associated nutrient content), digester configuration and operation, digestate storage and treatment should result in a digestate with minimal methane residue and available nutrients which needs to be recognised as a valuable fertiliser [64,65].

4.2.2. The CNG industry

Purchase of a CNG vehicle by an individual has to be based on the idea that the CNG vehicle will have a resale value. Construction of a CNG station (capital cost of the order of €300,000–€400,000) must be based on regular customers at a scale to pay back the investment. The first individual and the first service station developer are pioneers in a new industry; momentum is required to effect these investments. Thus a new market for CNG requires a definite transparent road map; it will also require legal agreements among the relevant actors (e.g. natural gas provider, CNG vehicle supplier, service station, biogas plant). Initiation may require subsidies for the first 10 refuelling stations and the first 1000 CNG vehicles. Symbiotic relationships abound, there will be no CNG car users without CNG service stations, without natural gas supplies, without government support of the industry. Of issue is the first step and who takes it.

An excellent first step is a captive fleet; this is typically associated with a bus service, municipal vehicles and/or a taxi fleet. At present there are over 400,000 CNG buses running in the world [17]. The fleet would be purchased at the same time as the construction of the refuelling facility. Yeh [35] stated that the number of CNG cars per refuelling station must be higher than 200:1 to allow a sustainable and profitable market; he further stated that the optimal ratio is 1000:1. At present Germany has a ratio of about 100:1 while Italy has a ratio of 1000:1 (Fig. 3). Flynn [66] highlighted the need for servicing and maintaining CNG vehicles in existing vehicle service centres. Charges for service and parts for CNG vehicles should not exceed those of the existing car fleet [66].

5. Roadmap for Ireland

Table 5 outlines a roadmap process for both the biomethane industry and the CNG industry broken into three 5-year intervals. There are a number of important environmental targets that Ireland must achieve. The most immediate include the target of 50% and 65% reduction of organic waste landfill by 2013 and 2016, respectively [67], the 10% RES-T by 2020 [7] and the 20% reduction in GHG emissions by 2020 based on 2005 emissions [4]. These are the drivers for the bio-CNG industry and are the rationale for Government support through legislation and policy. Grid injection of biomethane should be operational with support through tariffs and policy before the Landfill Directive comes into force in 2013. This will facilitate OFMSW biomethane and the sale of renewable gas from 2013. Targets for up to 2020 for biomethane as a proportion of natural gas should be set taking into account the potential

Table 5
Roadmap process for bio-natural gas industry in Ireland.

Period	Policy support	Expected outcomes
2011–2015	**Biomethane industry** Policy, regulations and appropriate grants to facilitate the development of biogas and biomethane upgrading facilities Set an appropriate tariff and target for 2020 for biomethane injection into the gas grid Construct an urban demonstration biomethane facility complete with gas grid injection	**Biomethane industry** Develop a number of OFMSW digesters at significant scale (ca. 50,000 $t\,a^{-1}$) complete with grid injection Facilitate compliance with 2013 Landfill Target Sale of renewable gas by 2013
	Gas for transport Set an appropriate national target for CNG vehicles in public service fleet for 2020 Construct a demonstration CNG service station primarily for public service vehicles	**Gas for transport** A demonstration facility highlighting public service vehicles, buses and commercial fleets operating on CNG
2016–2020	**Biomethane industry** Policy, targets and tariffs to encourage agricultural sector to invest in biomethane industry at centralised anaerobic digestion (CAD) facilities at a scale to allow cost effective grid injection Construct a demonstration agricultural based CAD facility with grid injection	**Biomethane industry** Growth in the number of biogas facilities treating OFMSW to allow compliance with Landfill Target for 2016 An increasing number of rural CAD facilities with upgrading facilities developed injecting biomethane to the gas grid Increased sale of renewable gas
	Gas for transport Incentive purchase of CNG vehicles Incentivise installation of home-refuelling systems Set an appropriate price structure for retail gas as a transport fuel Extend the number of public filling stations	**Gas for transport** Increased proportion of public service vehicles, taxis and commercial fleets running on bio-CNG An appropriate growth rate of CNG vehicles to meet the 2020 target
2021–2025	**Biomethane industry** Evaluate the success or otherwise of the industry and modify existing tariff structure and incentive policy if required	**Biomethane industry** Number of biogas facilities and biomethane upgrading facilities to meet the biomethane injection target for 2020
	Gas for transport Evaluate the role of biomethane in compliance with the 2020 RES-T target Evaluate the success or otherwise of gas powered public service vehicles Monitor the improvement of air quality in urban centres Consider the bioresource and cost associated with increased targets for gaseous fuel	**Gas for transport** Increased penetration of CNG vehicles and associated CNG service stations Optimal ratio of vehicles to service stations of 1000:1

resource (Table 1). Appropriate grants should be made available to support the initiation of the industry. The expanded biogas industry should encourage the agricultural sector to invest in centralised anaerobic digestion (CAD) facilities. Good practice would include for urban and agricultural demonstration projects complete with gas grid injection.

In Ireland in 2009 the energy requirement of public service vehicles (buses and taxis) accounted for 4.9% of total energy in road transport [2]. Filling this market with biomethane would equate to 9.8% RES-T (Table 1). The existing EVs scheme which focuses on passenger cars is predicted to contribute 1% RES-T in 2020. Thus 10% RES-T could be met indigenously.

For the industry to thrive passenger cars must become part of the process. The price structure for retail vehicle gas should at least allow a short payback period to cover any extra cost of a CNG vehicle. A number of incentives should be associated with purchase of new CNG cars, such as: Vehicle registration tax (VRT) relief; incentivisation of home refuelling systems; continued excise relief scheme for CNG. Training schemes are required for after-sale services; sufficient service providers are essential [66]. Post 2020, the extent and success (or otherwise) of the gaseous fuel industry coupled with the improvement of air quality in urban centres should be assessed for consideration of further targets.

6. Conclusions

Ireland is committed to a number of environmental targets, including the national GHG reduction of 20% relative to 2005 by 2020, landfill reduction of 65% by 2016, and 10% market share of renewable energy in transport by 2020. The introduction of biomethane can help to meet these targets. Ireland has a readily available resource in biomethane production of 8.4% of transport energy. This level of oil replacement with biomethane would directly save €500 m a^{-1} from imports, provide an injection of €500 m a^{-1} into the Irish economy and save a further €22 m a^{-1} in the reduced damage cost of traffic-related pollutant. A biomethane transport fuel market is predicated on a CNG market. An extensive natural gas infrastructure is in place in Ireland connecting to over 40% of houses. Development of this industry in Ireland requires strong government commitment. For example, the EU has enhanced the CNG market through excise relief. In some Germany municipalities taxis get special rates for CNG. In Sweden CNG vehicles are exempted from congestion tax; CNG vehicles may also avail of free parking in cities. Recommended supports include: policy dictating that all new buses run on gaseous fuel; setting a market penetration target for CNG vehicles; mandation of biomethane as a proportion of gaseous transport fuel, subsidies for biomethane facilities and grid injection.

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